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Windows in the buildings of tomorrow: Energy losers or energy gainers?

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ABSTRACT

One of the most effective actions for reduction of energy loss through the building envelope is to optimize the thermal performance, area and localization of the transparent components in the façade in order to obtain minimal heat losses and optimal solar gains.

When considering the thermal performance of these transparent components, one should consider, not only heat loss (or gains) caused by thermal transmission, but also the beneficial effects of incident solar radiation and hence reduced demand for heating and artificial lighting.

This study presents calculations for a range of windows as part of a building where the coupled effects of incident solar radiation and thermal transmission heat losses are accounted for in terms of a net energy balance for the various solutions. Effects of varying thermal transmittance values (*U*-values) are studied in connection with solar heat gain coefficients.

Three different rating methods have been proposed and applied to assess the energy performance of several window configurations. It has been found that various rating methods give different energy saving potentials in terms of absolute figures. Furthermore, it has been found that windows, even with existing technology, might outperform an opaque wall in terms of heating and cooling demands.

1. Introduction

Energy demand in the building stock in Norway represents about 40% of the final energy consumption [1]. A substantial part of the energy use in the construction sector is directly related to the construction, operation and decommissioning of the actual buildings. The energy consumption is to a large extent related to the heating and cooling demands as well as lighting demands.

Previous studies show that a large part of the heat loss in buildings occurs through the glazed parts of the envelope. Grynning et al. [2] found that the heat loss related to windows contributes over 40% of the total heat loss through the building envelope for a typical Norwegian office building constructed according to the present Norwegian building regulations, known as TEK 10 [3]. The total heat loss distribution, excluding the ventilation heat loss, is shown in Fig. 1.

Based on the recommendations given in IEA ECBCS Annex 44 and the "Kyoto Pyramid" [4] combined with the fact that windows contribute to a substantial part of the heat losses one should further investigate the possibilities of reducing the heat loss related to all glazed and translucent parts of the facades. In addition, the glazed areas can give a positive contribution to the energy balance of the buildings by letting solar energy through, into the buildings and reduce heating demands during some periods. However, the use of glazed parts and components in a facade can also give raise to a cooling demand in the building.

In this article the combined effects of heat loss and heat gains are analyzed for a typical Norwegian office building. A parametric study have been performed using the building energy simulations (BES) modeling tool EnergyPlus [5] where the thermal transmittance (*U*-value) and solar heat gain coefficient (SHGC), also known as solar factor (SF), have been varied arbitrarily to investigate the effects they have on the energy balance of the windows using three distinct rating methods. One of the three methods, being the resulting heating and cooling demand for the building as function of *U*-value and SHGC combinations are also presented.

2. Window heat transfer

2.1. Window heat transfer mechanisms

The total heat flows through a window consist of conduction, radiation and convection driven by a temperature difference. Heat transported by conduction, long-wave radiation and convection is in general related to the total *U*-value of the window. Solar

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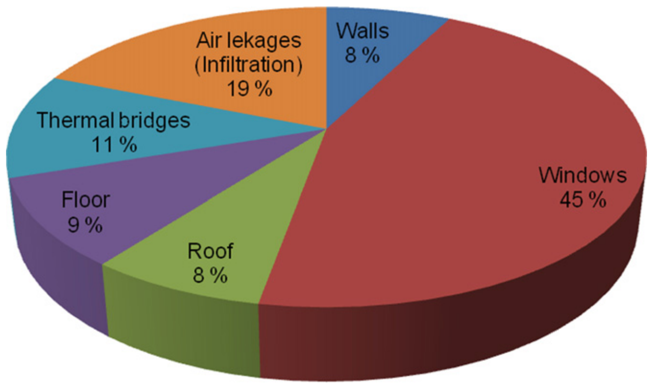

Fig. 1. Percentual distribution of heat losses through the various building envelope parts of an office building built according to the present Norwegian building regulations [2].

short-wave radiation will also be a large contributor to the heat flows, and is related to the SHGC of the window. The general energy transfer equation for a window is given in Eq. (1). The transmission heat flows, short-wave radiation contribution and the effect it has on artificial lighting demands are accounted for.

$$q_{\text{window,tot}} = q_{\text{transmission}} - \eta_{\text{shading}} \cdot q_{\text{sol}} - \Delta\xi_{\text{daylighting}} \tag{1}$$

where $q_{\text{window,tot}}$ is the total window energy balance (W/m^2), $q_{\text{transmission}}$ the Window transmission heat flow (W/m^2), η_{shading} the efficiency of shading system, q_{sol} the solar radiation level (W/m^2), $\Delta\xi_{\text{daylighting}}$ is the decrease of artificial lighting demand due to daylight (W/m^2).

2.2. Window energy performance – state-of-the-art

Numerous methods for rating window energy performance have been proposed in the existing literature. They range from very simplified methods where only the heating dominated period of the year is investigated to whole building specific numerical models of energy performance. The most relevant studies and methods are summarized below.

Investigations and calculations of window energy performance have been performed in several studies (see Table 1). Residential buildings are the type of building that has been studied most often. Only a few of the studies discuss the energy performance of windows in office buildings. The effect of window distribution on the heating and cooling demand of the building has been investigated. However, the buildings studied, are relatively poorly insulated with high U-values and thus do not give a representative picture for a building constructed with a low-energy envelope (e.g. passive house levels). The window properties are also somewhat outdated with higher U-values and lower corresponding SHGCs than what is achievable and more common with today's state-of-the-art windows.

For office buildings it is especially interesting to investigate the presumed effect of windows on the cooling demand in more detail. This does, however, make the performance related to internal gains, geometry and any other terms in the heat-balance of the building more complicated. Furthermore, it can be made a clear distinction between residential and public buildings. Residential buildings differ from commercial buildings in several aspects. Here, two are mentioned. Firstly, residential buildings have lower internal gains. Secondly, in general, no cooling plant will be installed in residential buildings.

The fact that cooling demands can be neglected in a residential building reduces the complexity of a simplified model and makes the construction of such a model less cumbersome than a model for an office building where cooling demands usually constitutes a large part of the energy demand, as is the case even in a Nordic climate.

2.3. Performance rating methods

2.3.1. A Danish method

A net energy gain value for residential buildings, has been proposed in Denmark [14]. Here, they present a method to account for both heat losses and heat gains through a window based on the U-value and the g-value (the same as the SHGC). Where the net energy gain is defined as:

$$E = g \cdot I - U \cdot D \tag{2}$$

where E is the net energy gain (W/m^2), g the solar energy transmittance, I the solar radiation (W/m^2), U the thermal transmittance (U-value) (W/(m^2 K)), D is the degree-day-number (K).

The method proposed by the authors [14] is a simplified model, which is valid for the heating season only. Thus making it less suitable for buildings where a cooling demand is prominent during warmer periods of the year. In these periods solar gains might give a negative contribution to the energy balance of the building by increasing cooling demands.

2.3.2. A Spanish method

Spanish researchers [15] have presented a window energy rating system (WERS), where they studied the useful energy for heating of the building as function of climate and building type. Here, they present two distinct methods. The annual useful solar heat gains are used as the base for the window energy rating. The authors [16] define a characteristic parameter, the balance temperature, T_b, which is a function of solar radiation levels ($Q_{\text{sol,u}}$), internal gains (Q_{int}), the total heat losses (K_{tot}) and the time interval considered ($\Delta\tau$), as given by:

$$T_b = T_{\text{int}} - \frac{Q_{\text{sol,u}} + Q_{\text{int}}}{K_{\text{tot}} \cdot \Delta\tau} \tag{3}$$

where T_b is the balance temperature (°C), T_{int} the indoor temperature (°C), $Q_{\text{sol,u}}$ the useful solar gain for building heating-system (kWh), Q_{int} the heat gains from internal sources (kWh), K_{tot} the building heat loss coefficient (kW/K), $\Delta\tau$ is the time interval (h).

T_b is used to find the proportion between the useful and total solar heat gain. The equation is solved in an iterative process whilst simultaneously solving the equation for $Q_{\text{sol,u}}$, given by:

$$Q_{\text{sol,u}} = S_g(T_b) \cdot A_g \tag{4}$$

where $S_g(T_b)$ is the cumulative radiation up to temperature T_b (kWh/m^2), A_g is the glazing area (m^2).

Then the equation shown in Eq. (5) is applied to evaluate the energy gain through the windows for all time-steps, where the external temperature, T_{ext}, is lower than the balance temperature, T_b, given by:

$$E = \sum \frac{(A' \cdot g_o + B' \cdot \alpha_f \cdot U_f - D' \cdot U_T - C \cdot L_{75})}{\eta} \tag{5}$$

where E is the energy gain through windows (kWh/m^2), A' the geometric factor to adjust solar irradiance (kWh/m^2), g_o = g-value of glazing at normal incidence, B' the factor accounting for surface heat resistances (kWh/m^2), α_f the absorptivity of frame, U_f = thermal transmittance of frame (W/(m^2 K)), D' the factor accounting for indoor/outdoor temperature difference (kKh), U_T the thermal transmittance of the window (W/(m^2 K)), C is the factor transforming L_{75} to realistic pressure differences (kWh/m^3), L_{75} the window infiltration rate at 75 Pa pressure difference (m^3/(h m^2)), η the annual fuel utilization efficiency.

Table 1
Window energy performance studies. Investigated parameter details for SHGC, U_g (W/m^2 K) and $U_{envelope}$ (W/m^2 K).

Type of building	Investigated parameter details	Climate	Additional information	Reference
Residential	SHGC = 0.5 U_g = 2.9/1.7/1 $U_{envelope}$ = 0.43/0.18	Stockholm, Berlin and Madrid	Shading included	[6]
Low energy house	SHGC = ? U_g = 0.7 $U_{envelope}$ = 0.10	Gothenburg	Window size and distribution	[7]
Residential	SHGC = 0.4–0.6 U_g = 0.6–1.4 $U_{envelope}$ = 0.17–0.18	Paris, Milan, Nice and Rome	Glazing properties. Window size. Low and no internal gains	[8]
Residential	SHGC = 0.4–0.6 U_g = 0.6–1.4 $U_{envelope}$ = 0.17–0.18	Stockholm, San Francisco, Miami	U-value vs. low-e coatings	[9]
Residential	SHGC = 0.02–1 U_g = 0.11–5.68 $U_{envelope}$ = 0.15–0.5	Fresno, Washington, DC, Minneapolis, Charleston, Salt Lake City	2500 combinations presented as windows use energy or windows produce energy. Dynamic SHGC studied	[10]
Office building	SHGC = 0.2–0.7 U_g = 0.92–1.65 $U_{envelope}$ = 0.18–0.32	Gothenburg	Window distribution. Window size and U-/SHGC. Shading systems included	[11]
Residential	SHGC = 0.42–0.76 U_g = 1.1–2.5 $U_{envelope}$ = 0.08–0.47	Stockholm	Window size/distribution. Window properties	[12]
Office (single cell)	SHGC = 0.5–0.8 U_g = 0.94–2.61 $U_{envelope}$ = 0.18	Stockholm	Window size, direction, properties and daylighting	[12]
[1,0]Office (single cell)	SHGC = 0.16–0.86 U_g = 1.0–2.6 $U_{envelope}$ = 0.18	Lund, Stockholm, Luleå, Oslo, Montreal	Window size, direction, properties and daylighting Indoor climate, comfort	[13]

Hence, the fact that solar radiation might lead to a cooling demand when internal temperatures exceed that of the cooling set-point temperature is disregarded. Furthermore, they compare the proposed method with results using the building energy simulation (BES) tool TRNSYS [17]. They conclude that windows with a low emissivity coatings and high SHGC are desirable in a cold or temperate climate and that triple glazing units can give a greater energy savings in cold climates compared to temperate climates.

2.3.3. An Italian method

The authors [18] present three separate building cases which have been studied in order to introduce a rating scheme. Five different, Italian climates have been studied. The ratings proposed are functions of window properties, climate conditions and the architectural characteristics of the residential building. Both cooling and heating loads were considered with the use of detailed simulations using the BES tool TRNSYS [17]. The simulation results were used to define a simplified algorithm using different regression approaches which can be used to rate the window heating load reduction (HLR) and cooling load reduction (CLR) potentials.

A normalized HLR coefficient (NHLR) is defined which is based on the window transmission heat losses, infiltration heat loss caused by the windows in the building and the average winter solar radiation (R_{inv}) over the four cardinal directions. Similarly, a normalized CLR potential (NCLR) is proposed as function of U-value, g-value and air leakages.

The analysis has been performed on windows with U-values of 2.6 W/(m^2 K) and higher and it does not discuss how other building types and/or climate conditions would influence the rating factors found by the performed regression analysis. However, the authors point out that further investigations of the energy-rating schemes are required.

2.3.4. A Canadian method

Through the IEA SHC Task 27, a Canadian workgroup has proposed a simplified energy rating model for windows [19]. Here, they also present an overview of which parameters that must have a clear and specific measure in order to be able to characterize an energy efficiency level. The parameters are: U-value, SHGC, visible transmittance (T_{vis}) and condensation resistance. Based on these parameters a simplified equation is proposed (Eq. (6)), which is used to calculate the energy rating (ER).

$$\mathrm{ER} = 0.8 \cdot 72.2 \cdot \mathrm{SHGC} - 21.9 \cdot U_w - 0.54\frac{L_{75}}{A_w} \tag{6}$$

where ER is the energy rating (W), SHGC$_w$ the solar heat gain coefficient of a window, U_w the overall heat loss coefficient (W/m^2 K), 72.2 the factor to account for average solar radiation on a vertical window, during heating season (W/m^2), 0.8 the factor to account for exterior shadings on windows, 21.9 the average temperature difference over the heating season (°C), 0.54 the factor adjusting air leakages at 75 Pa pressure difference to real pressure average difference, L_{75} the air leakages related to the window at a 75 Pa pressure difference (Pa), A_w is the window area (m^2).

However, the rating method is valid only for the heating season, and the multiplication factors to account for average solar radiation, and temperature difference are calculated for Canadian climates only.

Furthermore, the author has performed simulations of energy consumption for a residential house as function of SHGC variations for the windows. The U-value was kept constant at 2.0 W/(m^2 K). It was found that a window with a SHGC in the range 0.3–0.4 gives the lowest energy demand. For a small commercial building it is concluded that a SHGC of 0.35 gives the cost-optimum solution.

2.3.5. Methods summary

Common for all the simplified methods proposed, is that all but the Italian method consider the energy balance during the heating season of the year only. This might be adequate for residential buildings, but not for buildings with cooling loads. Good performances during a period with a negligible cooling demand might not necessary indicate a good performance during the cooling dominated period of a year. It is a fact that office buildings with a large amount of transparent surfaces toward south will have a cooling demand during extensive periods of the year, even in a cold climate like, e.g. Norway [20].

Furthermore one can see a clear similarity between the Danish and the Canadian method. The energy rating for both methods revolves around accounting for solar gains as a positive contribution, and heat losses as a negative factor. The main difference is that the Canadian method accounts for air leakages related to the windows as a separate term.

The Danish, Spanish and Canadian methods, all describe simplified models with a somewhat generic usefulness, but they all have certain limitations in that they are applicable only to residential buildings where cooling loads are minor.

The Italian method describes the procedure for rating both the cooling and heating performance, but is limited in that it is based on regression analyses for only a limited number of climate conditions and windows with a high *U*-value of 2.6 W/(m^2 K).

3. Methods

3.1. Software, simulations and input values

Simulations for an entire year have been performed for a building using the BES software EnergyPlus [5]. A five minute time-step was used to perform the calculations. In the calculations, the effect of solar heat gains through windows and window heat loss on the heating and cooling demand of the office building has been considered. A study of *U*-value and SHGC variations has been performed. The *U*-values have been varied from 0.2 W/(m^2 K) to an upper limit of 1.2 W/(m^2 K). The upper level of 1.2 W/(m^2 K) is the upper limit for *U*-values that can be used in new buildings according to the Norwegian building regulations [3]. The SHGC has been varied in steps of 0.2 from a lower limit of 0.2 up to 0.8. The upper limit was set since reaching higher SHGC than 0.8 is not practically feasible due to reductions in transmittance by the glass itself.

Finally, a double-, triple-, and four-pane window have been constructed using WINDOW 6.0 [21]. The combinations of *U*-value and SHGC assessed using the three methods have been carried out with theoretical combinations of *U*-values and SHG coefficients. A combination of, e.g. low *U*-value and a high SHGC is not possible to obtain with existing materials and technology. Therefore, three state-of-the-art windows have been constructed and assessed applying the three methods. These windows represent the state-of-the-art for windows available on the market today. *U*-values and SHGC from the calculations have been used as input for rating the three windows using the three methods proposed in this work.

3.2. The office building in question

Simulations for an office building situated in Oslo (latitude, 59.91°N), Norway have been performed. The office building is a typical mid-size Norwegian building with a ground floor area of 1200 m^2 (30 m by 40 m, with the 40 m sides oriented north-south) and three stories, giving a total heated area, A_{BRA} = 3600 m^2. The window area was set to 690 m^2, equaling 20% of the A_{BRA} (this equals a window to wall ratio, WWR, of 55%). It is constructed so as to fulfill the Norwegian passive house standard for dwellings, NS 3700 [22]. This results in *U*-values for the roof, walls and floor of 0.13, 0.15 and 0.15 W/(m^2 K) respectively, and an airtightness of the envelope of 0.7 h^{-1} at 50 Pa pressure difference. Internal loads, ventilation schemes, operational hours, etc. have been set according to standard values for office buildings given in the Norwegian standard for energy performance calculations, NS 3031 [23]. A simplified three-zone model, as specified in NS 3031, for each of the floors has been used. This implies creating a 5 m deep sun-exposed zone to the south, a 20 m deep central zone and a third 5 m deep zone toward the north.

3.3. Model simplifications

The SHGC is in practice an angular dependent variable. Depending on glazing properties, the value of the SHGC will vary as function of solar height and azimuth. In this work the simplified model for windows implemented in Energy Plus has been used. The SHGC is given as a constant, non-angular dependent value as input to the simulation software.

Air leakages related to mounting of windows in walls might have a substantial effect on the total infiltration heat losses of a building. The mounting of windows are, however, not dependent on the glazing properties and is therefore not a variable when performing a parametric study on *U*-value and SHGC combinations. Based on this, all heat losses due to window air leakages have been disregarded in this work as they may be considered constant and thus have been included as a part of the total infiltration heat loss of the building.

The daylighting levels in a building will also influence the energy demand of the building. A high level of transmittance of visible light (T_{vis}) can lower the demand for artificial lighting. The effect different T_{vis} values of the glazing systems have on the demand for artificial lighting is not within the scope of this study. Nor have the effect of installing solar shading systems been studied in this work. This will be evaluated in later studies.

3.4. Window rating methods

The energy performance of the windows studied in this work has been rated by use of the three different approaches as listed below:

1. ISO 18292:2011; *Energy performance of fenestration systems for residential buildings – calculation procedure* [24].
2. The useful gain method (proposed below).
3. The effect on the combined cooling and heating demand of the building.

3.4.1. ISO 18292 method

The ISO 18292 [24] standard suggests a simplified method for assessing the energy performance of fenestration systems for residential buildings. For Norwegian residential buildings, local cooling in dwellings should be avoided in new buildings erected in accordance with the present Norwegian building regulations [3]. Application of the method to an office building has nevertheless been made. The method gives two separate rating factors; a cooling rating factor p_c and a heating rating factor p_h. The factors are an indication on how the window system affects the energy demand of the building and are given on the form kWh/(m^2 window area and year). That is, a negative factor indicates a reduction of cooling or heating demand and is thus beneficial in terms of energy savings. An adiabatic element, with zero heat loss and zero heat gain, replacing the window is the reference element used in this method.

For ease of comparison to the other two methods proposed, the figures in this article have been converted into a rating factor

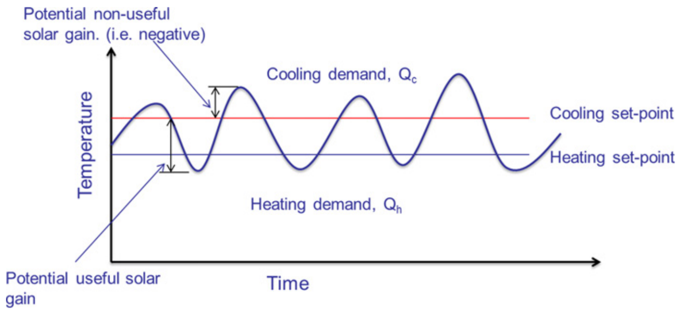

Fig. 2. Schematic illustration of potential usefulness of solar gains as function of internal temperature and cooling and heating set-point temperatures.

per m^2 floor area, A_{BRA}, thus giving figures in the following format kWh/(m^2 A_{BRA} year).

3.4.2. Useful gains method

The second method proposes a performance rating method where a defined useful gains factor is studied. Combined with the heat losses of the window this gives an assessment of the usability of any solar heat gains that enter via the windows and the useful energy balance of the windows.

Heat losses through windows contribute to an increased energy demand, when the building is in demand for heating. On the other hand, solar gains might contribute to reduce the energy demand for heating the building. The solar heat gains might lead to an increased cooling demand, thus contributing to an additional energy demand of the building. Fig. 2 shows a schematic illustration of this.

Fig. 2 shows an arbitrary temperature cycle as function of time. If the temperature exceeds the cooling set-point temperature, a cooling demand is induced. If at the same time, there are solar gains present, these will be considered non-useful (i.e. negative) as they contribute to the cooling demand. Depending on the ratio of the cooling demand to the solar gain level, two zones may be defined, as discussed in the following.

If the temperature drops below the cooling set-point temperature, all solar gains are considered useful (i.e. positive). This correlates to the third zone for the usefulness of the gains as discussed in the following. Considering all of these gains as useful is arguable. Some of the gains will directly contribute to heating the building and help to rise the temperature toward, up to or past the heating set-point temperature, whereas some gains will only shift temperatures within the comfort zone (i.e. between heating and cooling set-point temperatures). An additional effect not accounted for in the proposed method is that temperature shifts due to solar heat gains could influence the cooling demands when the set-back for heating and cooling are shifted at the end and start of operational hours.

Based on the previous discussion, three characteristic zones for the *usefulness* of the solar heat gains are defined:

1. Cooling demand > solar gains (e.g. cooling demand of 200 W and a solar gain of 100 W)
2. Cooling demand < solar gains (e.g. cooling demand of 100 W and a solar gain of 200 W)
3. No cooling demand

Based on these three zones one can define a useful gain factor at a time-step i, $q_{ug,i}$, as shown in Eq. (7), for each zone.

1. All solar gains are considered negative $\Rightarrow q_{ug} = -$solar gains
2. The cooling demand part of the solar gains is considered negative $q_{ug} = -$cooling demand
3. All solar gains are considered positive $\Rightarrow q_{ug} =$ solar gains

The useful gain can then be combined with the heat loss through the window to give the useful energy balance of the window, $Q_{window,useful}$, as shown in Eq. (7). It is noted that this evaluation has to be performed for each time step of the simulations performed and for each of the zones of the building.

$$Q_{window,useful} = \sum((q_{ug,i} - q_{loss,i}) \cdot \Delta T) \quad (7)$$

where $Q_{window,useful}$ is the useful energy balance for windows (kWh/(m^2 A_{BRA} year)), $q_{ug,i}$ the useful solar gain through window at time-step i (J/(m^2 A_{BRA})), q_{loss} the heat loss through window at time-step i (J/(m^2 A_{BRA})), Δt is the simulation time-step length (s).

To ensure coherence with the ISO 18292 method and ease of comparison of results the useful gain is defined as being beneficial in terms of reduction of energy demand. Thus negative values for the useful gains and useful energy balance will give a reduction of heating and cooling demands. As for the ISO 18292 method, simulated values are given per m^2 heated floor area (kWh//(m^2 A_{BRA} and year)). One can easily convert the numbers to a per-window area basis by multiplying with the heated floor area (m^2) and dividing on the window area (m^2).

3.4.3. Cooling and heating demand method

The third approach for assessing the energy performance of the windows was performed by studying the heating and cooling demand of the building as function of U-value and SHGC variations. A case, where all windows are replaced with an opaque wall (with the same U-value as the rest of the building) was used as a reference comparison case. As for the other two methods, simulated heating, cooling and combined heating and cooling are stated on a per square meter heated floor area.

4. Results and discussion

4.1. ISO 18292 method

The application of the ISO 18292 method shows that the windows give a beneficial contribution to the heating demand of the building for most combinations of U-value and SHGC. The y-axis of the graphs shown in Figs. 3–5 gives values for how the windows influence the heating, cooling or combined heating and cooling demand. Thus, negative values indicate that the window reduces the net demand.

From Fig. 3, we see that a window with a SHGC of 0.6 gives the lowest (most beneficial) possible heating performance contribution for the windows with U-values of 0.6 W/(m^2 K) and lower. Increasing the SHGC further gives a decrease to the heating performance.

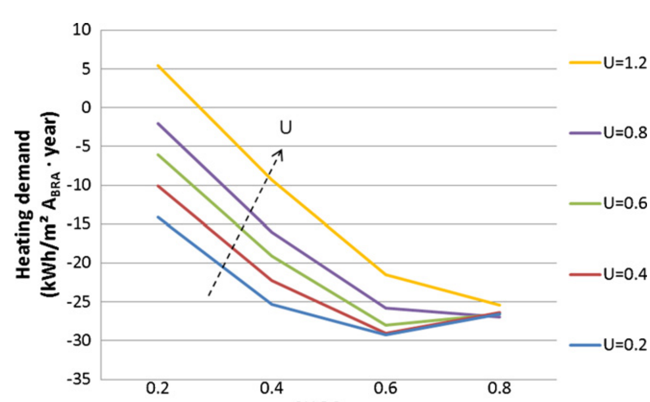

Fig. 3. Heating demand (performance) of windows (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

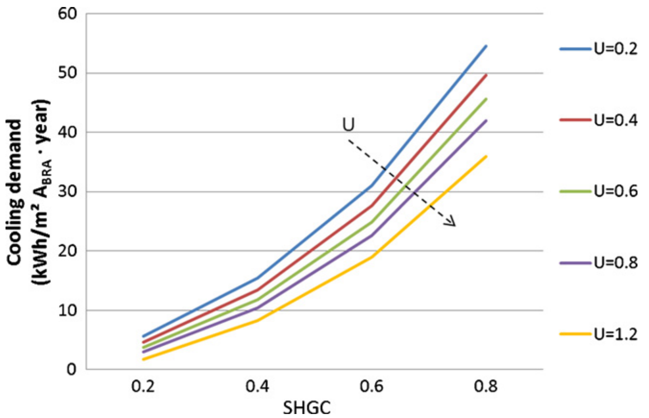

Fig. 4. Cooling demand (performance) of windows (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

From Fig. 4, one can see that an increase of the SHGC gives a significant increase in the cooling demand for the building.

If one look at the combined effect on both cooling and heating demand of the building, we see from Fig. 5, that an optimum window configuration with a SHGC = 0.4 and a U-value = 0.2 W/(m^2 K) gives the lowest possible performance rating factor. Windows with a U-value of 1.2 W/(m^2 K) combined with SHGC between approximately 0.38 and 0.64 results in configurations that can reduce the energy demand of the building. This method also shows that U-values lower than 0.8 W/(m^2 K) combined with a SHGC between 0.2 and 0.6 gives a negative (i.e. beneficial) performance rating.

4.2. Useful gains method

The second method shows the energy balance of the windows, as discussed in the methodology chapter. It is noted that to make figures coherent with the ISO 18292 method, the term useful gains are used with reference to reduction of energy demand. Popularly speaking, this means that a negative useful gain means one can subtract that figure from the energy bill, thus making it useful.

The amount of useful gains depicted in Fig. 6 shows that large solar gains in general must be associated with a cooling demand, thus increasing the energy demand of the building. Furthermore, one can see that a SHGC of 0.4 gives the optimal window configuration regardless of U-value when considering the useful gains (for this particular building and climate). If the SHGC is higher than 0.4, cooling demands reduce the amount of useful gains. SHGC

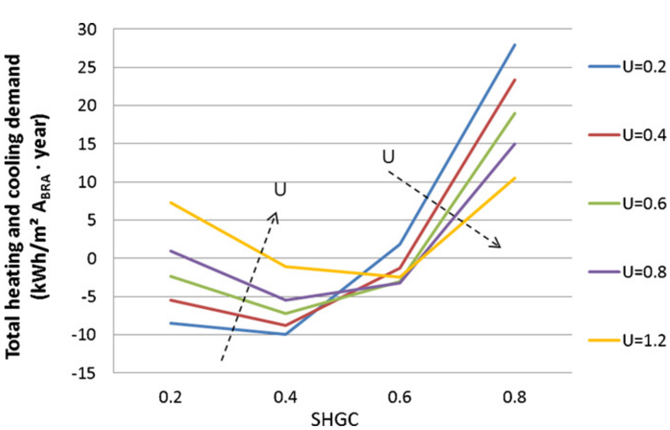

Fig. 5. Combined heating and cooling demand (performance) of windows (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values calculated according to procedure given in ISO 18292 [24].

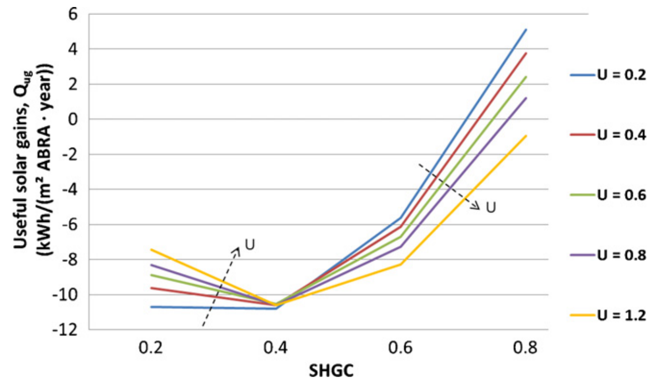

Fig. 6. Useful solar gains ($Q_{ug} = \sum(q_{ug,i})$) from the window distributed on the heated floor area (kWh/(m^2 A_{BRA} year)) for Oslo climate.

lower than 0.4 gives higher heating demands and thus reduces the amount of useful gains.

Fig. 7 shows the defined useful energy balance of the windows according to the useful gains method. Several U-value and SHGC combinations will in theory give windows that reduce the energy demand of the building. In the same figure, the energy balance of an opaque wall is shown. The opaque wall will always be associated with a heat loss, since no solar gains are practically achievable. A window with U-value 0.6 W/m^2 K and SHGC of 0.6 has the same useful energy balance as an opaque wall. For even lower U-values it is possible to have windows that give a positive contribution to the energy balance of the building. This makes it a *net energy gainer* according to the proposed method. Following the same trend as the useful gains showed in Fig. 6, the useful energy balance reaches an optimum for a SHGC of 0.4.

4.3. Heating and cooling demand rating

In the following, we see how the heating and cooling demand of a building varies with the U-value and SHGC-values for the windows. In Figs. 8–10, the energy demand for heating, cooling and the combined heating and cooling divided on the heated floor area of the building are shown.

From Fig. 8, we see a drop in heating demand, as function of a reduced U-value and an increasing SHGC value. Focusing solely on the heating demand suggests that low U-values combined with high SHGC values should be aimed at. Furthermore, it is shown that the heating demand can be reduced by more than 50% for the windows with the lowest U-values compared to the reference case where the windows have been replaced with an opaque wall with the same U-value (0.15 W/m^2 K) as the rest of the walls.

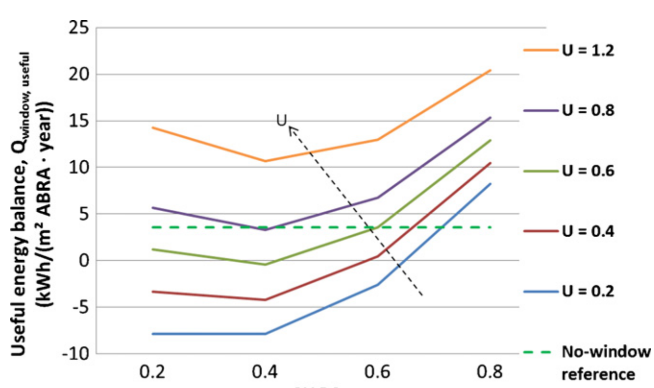

Fig. 7. Useful yearly energy balance of the window ($Q_{window,useful}$) distributed on the heated floor area (kWh/(m^2 A_{BRA} year)) as calculated from Eq. (4) for Oslo climate.

Table 2
Comparison of energy savings potential for three windows using the proposed methods.

	Energy demand saving potential (kWh/(m^2 A_{BRA} year))		
	ISO 18292	Useful gains method	Heating and cooling demand[a]
2-Pane window U-value/SHGC = 1.2/0.50	−2	12	45(10)
3-Pane window U-value/SHGC = 0.8/0.34	−4	4	35(3)
4-Pane window U-value/SHGC = 0.4/0.28	−7	−4	32(−3)

[a] Figures in brackets show the heating and cooling demand for the window configuration compared to (subtracted from) the heating and cooling demand of the opaque wall reference case. Hence, the four-pane window will act as a *net energy gainer* compared to an opaque wall.

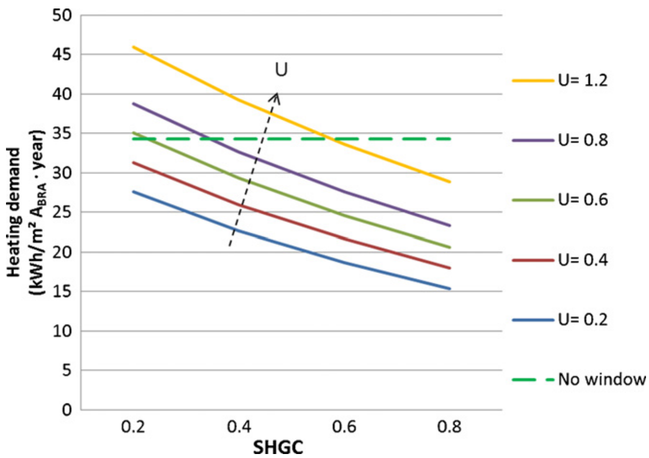

Fig. 8. Heating demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

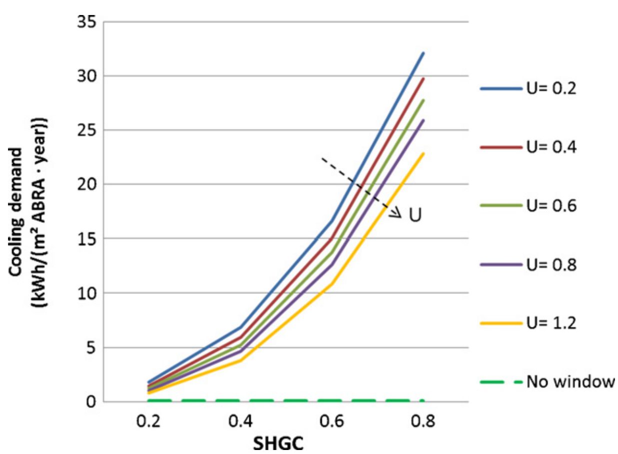

Fig. 9. Cooling demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

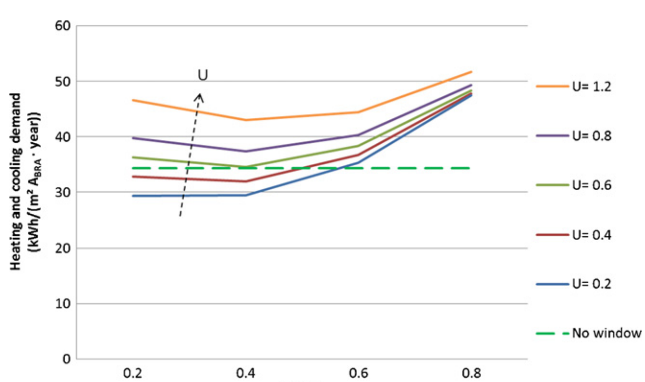

Fig. 10. Combined sum of heating and cooling demand for office building (kWh/(m^2 A_{BRA} year)) for Oslo climate. Values from EnergyPlus simulations.

In contradiction to the heating demand, the introduction of a cooling demand, as shown in Fig. 9, suggest that one should decrease the SHGC values as much as possible to reduce cooling demands. The largest energy savings potentials are for high SHGC values. The gradients of the curves lessen when the SHGC are approaching 0.2.

When summing up both heating and cooling demands, we see similarities in the performance to both the ISO 18292 method and the useful gains method. As shown in Fig. 10, the combination of a lowest possible U-value and a SHGC value of 0.4 give the lowest combined heating and cooling demand. Fig. 10 shows that windows with a U-value lower than 0.4 W/(m^2 K) and SHGC below approximately 0.5 will give a net heating and cooling demand lower than for the reference case where windows are replaced with an opaque wall.

4.4. Comparison of results from different methods

The three methods show somewhat incoherent results regarding the energy performance of the building and the studied window configurations. In general, the ISO 18292 method gives the highest energy savings potential for the windows. A combination of SHGC < 0.6 combined with any U-value gives a combined heating and cooling demand below zero, i.e. defining them as gainers.

Fig. 10, representing a combined sum of heating and cooling demand, shows that it is possible to reach a lower energy demand by use of windows rather than an opaque wall. The method does not, however, show the energy balance of the windows.

The second method utilizing the useful gains definition gives more conservative results than the ISO 18292 method. Windows with U-values below 0.4 combined with SHGC below 0.6 can, according to the results in Fig. 7, be classified as energy gainers.

All the three methods show that an optimal SHGC of the windows can be found. For the studied building, the most beneficial combination of U-value and SHGC is found with SHGC of 0.4.

Table 2 shows a comparison of the energy savings potential ratings using the three methods for three state-of-the-art windows.

Table 2 demonstrates that the three methods give different energy demand saving potential for all three windows. The difference is largest for the double-pane window, but the discrepancy is still high for the four-pane window. Nevertheless, regardless of method, it was found that a four-pane window will give a beneficial impact on the energy demand compared to an opaque wall.

5. Conclusions

The energy balance of a window and the effect of window properties on the energy demand of a building is a complex interaction of a large array of parameters. Previous studies show only the heat loss factors for building components and performance during the heating season of a year. This gives a biased impression of the window energy performance as it does not take into account any cooling demands of the building as a result of the window properties.

The results from the simulations carried out in this work show that cooling demands are dominating in office buildings even in what is commonly considered to be a heating-dominated cold climate like Oslo in Norway.

Three methods have been proposed and used to assess the energy performance of windows in an office building. The three methods give different energy savings potential in terms of absolute figures. The ISO 18292 method gives an optimum solar heat gain coefficient (SHGC) of 0.4 for windows with U-values lower than $0.8\,W/(m^2\,K)$. The other two methods suggest that low U-values combined with SHGC around 0.4 are desirable also in a cold climate due to substantial cooling demands.

Typical state-of-the-art windows available on the market today, can reach U-values as low as $0.4\,W/(m^2\,K)$ whilst still maintaining a SHGC of approximately 0.3, using a four-pane glazing unit. This makes them equal to or even better performing than highly insulated opaque walls with respect to the total heating and cooling demand. These windows may then be classified as *net energy gainers*.

Furthermore, it was found that a reduction of the window U-value from 1.2 to $0.8\,W/(m^2\,K)$ (i.e. going from a double to a triple pane insulated glazing unit) can reduce the energy demand for heating and cooling with 5–15% depending on the SHGC. Other building configurations may lead to in different results.

The introduction of dynamic solar shading systems is vital to lower the energy demands further than what is possible with unshaded windows.

6. Further work

The simulations performed in this work should be considered as the first phase of a work assessing energy performance of windows in office buildings. The useful energy balance of the windows may be used as input also for life cycle assessment (LCA) investigations. Further studies will include implementing dynamic solar shading systems and the effect of solar radiation on the artificial lighting demand. Control strategies and state-of-the-art systems should be investigated. Glare effects and comfort should also be included to give a better understanding of how shading systems affect, not only thermal performance, but also both the thermal and visual comfort in office buildings. New technologies for lighting (LED lighting) and technical equipment producing less heat are developing rapidly. This influences internal gains for office buildings even more. The effects of a reduction of cooling and heating demand should also be investigated.

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